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ScienceDirect
Continental Shelf Research 28 (2008) 112–136
CONTINENTAL SHELF RESEARCH
www.elsevier.com/locate/csr

A three-dimensional biophysical model of *Karenia brevis* dynamics on the west Florida shelf: A look at physical transport and potential zooplankton grazing controls

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Received 26 May 2004; received in revised form 10 January 2007; accepted 10 April 2007
Available online 22 July 2007

Abstract

The development of accurate predictive models of toxic dinoflagellate blooms is of great ecological importance, particularly in regions that are most susceptible to their detrimental effects. This is especially true along the west Florida shelf (WFS) and coast, where episodic bloom events of the toxic dinoflagellate *Karenia brevis* often wreak havoc on the valuable commercial fisheries and tourism industries of west Florida. In an effort to explain the dynamics at work within the maintenance and termination phases of a red tide, a simple three-dimensional coupled biophysical model was used in the analysis of the October 1999 red tide offshore Sarasota, Florida. Results of the numerical experiments indicate that: (1) measured and modeled flowfields were capable of transporting the observed offshore inoculum of *K. brevis* to within 16 km of the coastal boundary; (2) background concentrations (1000 cells L^{-1}) of *K. brevis* could grow to a red tide of over 2×10^6 cells L^{-1} in little more than a month, assuming an estuarine initiation site with negligible offshore advection, no grazing losses, negligible competition from other phytoplankton groups, and no nutrient limitation; (3) maximal grazing pressure could not prevent the initiation of a red tide or cause its termination, assuming no other losses to algal biomass and a zooplankton community ingestion rate similar to that of *Acartia tonsa*; and (4) the light-cued ascent behavior of *K. brevis* served as an aggregational mechanism, concentrating *K. brevis* at the 55 $\mu E\, m^{-2}\, s^{-1}$ isolume when mean concentrations of *K. brevis* exceeded 100,000 cells L^{-1}. Further improvements in model fidelity will be accomplished by the future inclusion of phytoplankton competitors, disparate nutrient availability and limitation schemes, a more realistic rendering of the spectral light field and the attendant effects of photo-inhibition and compensation, and a mixed community of vertically-migrating proto- and metazoan grazers. These model refinements are currently under development and shall be used to aid progress toward an operational model of red tide forecasting along the WFS.

Keywords: Mathematical models; Red tides; Algal blooms; Phytoplankton; *Karenia brevis*

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0278-4343/$ - see front matter
doi:10.1016/j.csr.2007.04.013

1. Introduction

The development of accurate predictive models of toxic dinoflagellate blooms is of great ecological and financial importance, particularly in regions that are most susceptible to their detrimental effects. This is especially true along the west Florida shelf (WFS) and coast, where episodic bloom events of the unarmored dinoflagellate *Karenia brevis* (= *Gymnodinium breve*, *Ptychodiscus brevis*) can cause mass mortalities of over 100 species of marine life (Steidinger and Ingle, 1972; Steidinger, 1983; Sakamoto et al., 1987), the results of which often wreak havoc on the valuable commercial fisheries and tourism industries of west Florida. The red tide organism *K. brevis* has been linked to these mortalities either directly due to the production and release of a variety of neurotoxins (Shimizu et al., 1995) or indirectly due to the depletion of dissolved oxygen during respiration (Simon and Dauer, 1972). The bioaccumulation of sub-lethal brevitoxins in fish and mollusk tissues has led to significant dolphin and seabird mortalities (Steidinger and Haddad, 1981) and has even been linked to neurotoxic shellfish poisoning (NSP) in humans (Shimizu et al., 1986). Brevitoxins released from lysed cells may also become airborne, and in the presence of breaking waves and/or onshore winds, may cause severe respiratory irritation to humans along the coast (Pierce et al., 1990). Thus, when considering the multitude of ecological, commercial, and public health hazards associated with these blooms, a reliable model of *K. brevis* population dynamics could be used to forecast the severity, location, and subsequent transport of red tides in an effort to mitigate ecological and financial losses incurred therefrom.

Until recently, the causative elements that underlie the initiation and dispersal of red tides had remained enigmatic. While several paradigms have been developed in past decades, they have all sought to reduce the complexities of toxic dinoflagellate ecology to a simple index of one or very few requisite environmental predictors. To date, red tides have been linked to the anthropogenic eutrophication of coastal waters (Satsmadjis and Friligos, 1983; Cannon, 1990; Pagou and Ignatiades, 1990), increased estuarine efflux (Chew, 1956), warm temperatures (Chew, 1956; Fraga et al., 1990; Pagou and Ignatiades, 1990), salinities of 21–37 psu (Rounsefell and Dragovich, 1966; Wilson, 1967), periods of decreased vertical mixing (Margalef et al., 1979; Cannon, 1990; Wyatt, 1990), and proximity to density fronts (Margalef et al., 1979; Taft and Martin, 1986; Fraga et al., 1990; Franks, 1992).

However, several investigations of *K. brevis* bloom dynamics in the eastern Gulf of Mexico and on the WFS have indicated that *K. brevis* is not normally a coastally occurring species. Rather, it is indigenous to oligotrophic shelf waters (Steidinger and Haddad, 1981; Tester and Steidinger, 1997), where blooms are instead thought to originate 18–74 km offshore (Steidinger, 1973; Steidinger, 1975; Steidinger and Haddad, 1981) since the nutrient-replete conditions in nearshore waters will instead favor blooms of diatoms and other phytoplankton competitors (Walsh et al., 2003).

While previous one-dimensional (Penta, 2000) and three-dimensional (Walsh et al., 2001, 2002, 2003) models have offered a great deal of insight into *K. brevis* dynamics on the WFS, it is difficult to embark upon exhaustive ecological simulations without a robust data set to initialize and validate such models. Fortunately, hydrographic data from several cruises on the WFS during August–November 1999 were available for the development of these models, including measures of:

(1) Biophysical and biooptical oceanographic parameters, such as temperature, salinity, density, light attenuation, and transmission (Ecology and Oceanography of Harmful Algal Bloom—ECOHAB, Mote, NEGOM, HRS, HyCODE);
(2) *In situ* nutrient concentrations, including ammonia, nitrate, nitrite, phosphate, silicate, and dissolved organic nitrogen–DON (ECOHAB, Mote, NEGOM);
(3) *In vivo* chlorophyll-*a* data (ECOHAB, Mote, NEGOM);
(4) Offshore and coastal *K. brevis* cell counts (ECOHAB, Mote, FMRI); and
(5) Zooplankton diversity, biomass, and abundance (HRS, ECOHAB).

Indeed, red tide dynamics on the WFS have been shown to be anything but simple, requiring a complex analysis of the biological, chemical, and physical contributions *in toto*. Walsh et al. (2006) have elucidated several complex requisites for the successful competition of *K. brevis*, whereby the initiation and persistence of red tides follow a strict chronology, requiring:

(1) A mid-shelf, phosphorus-rich nutrient supply (at low dissolved inorganic nitrogen (DIN)/dissolved inorganic phosporus (DIP) ratios)